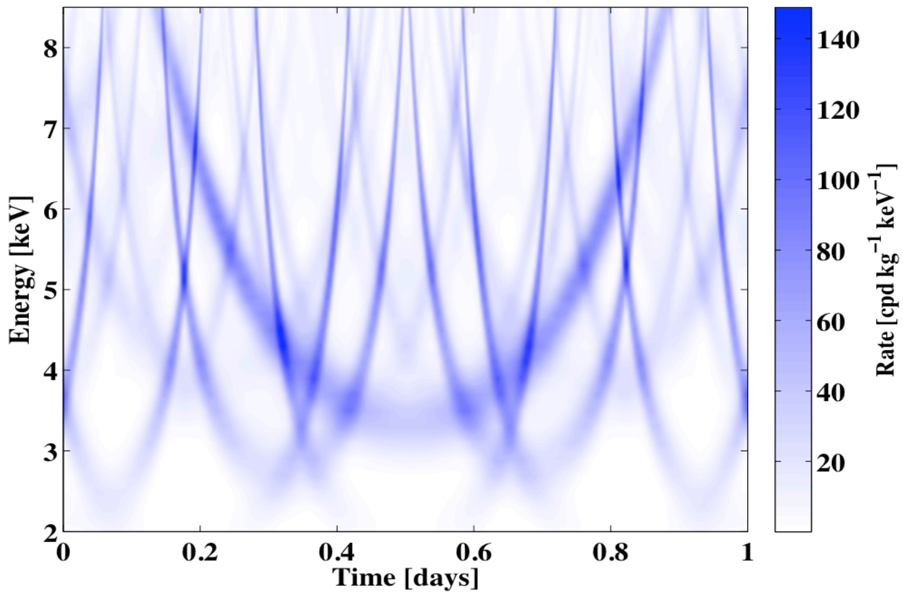
Solid Xenon

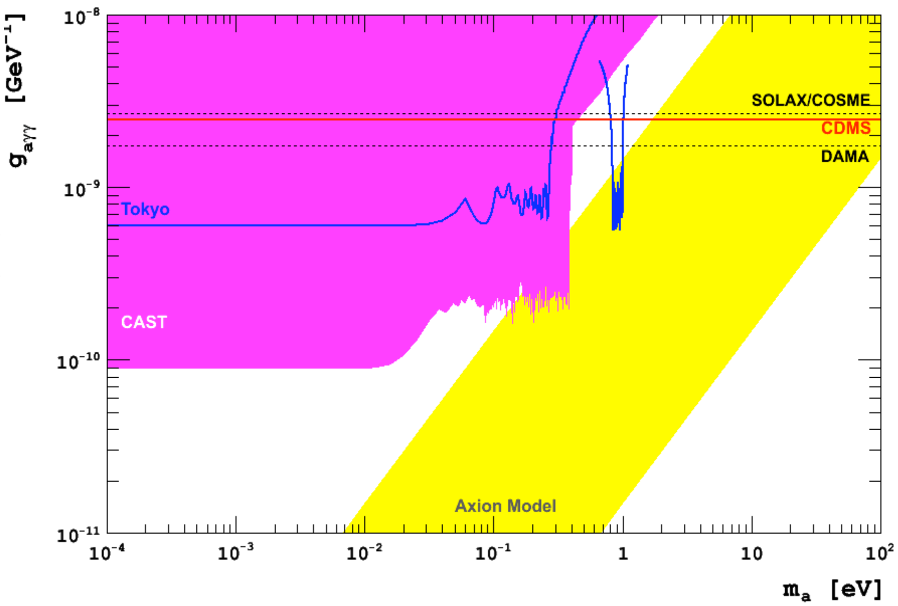
Jonghee Yoo

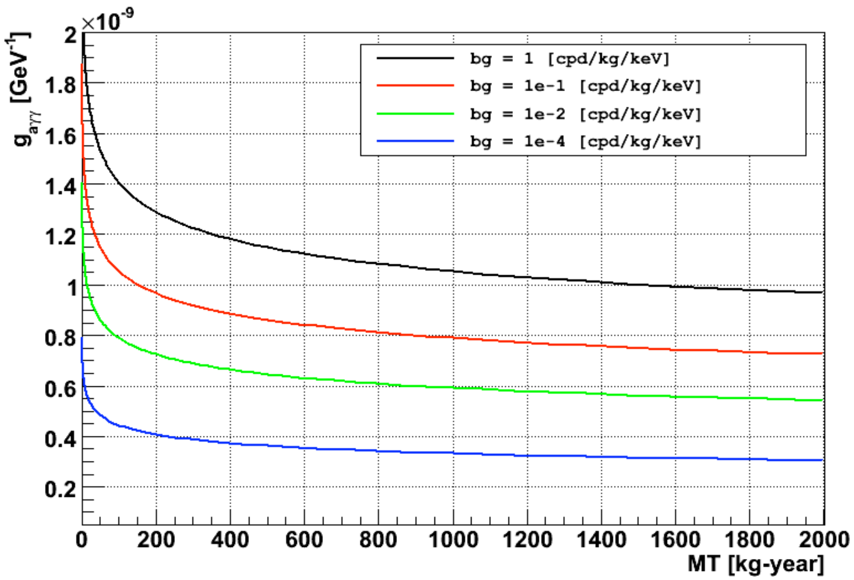
Fermilab Center for Particle Astrophysics Retreat
18 April 2009

CDMS Axion Search



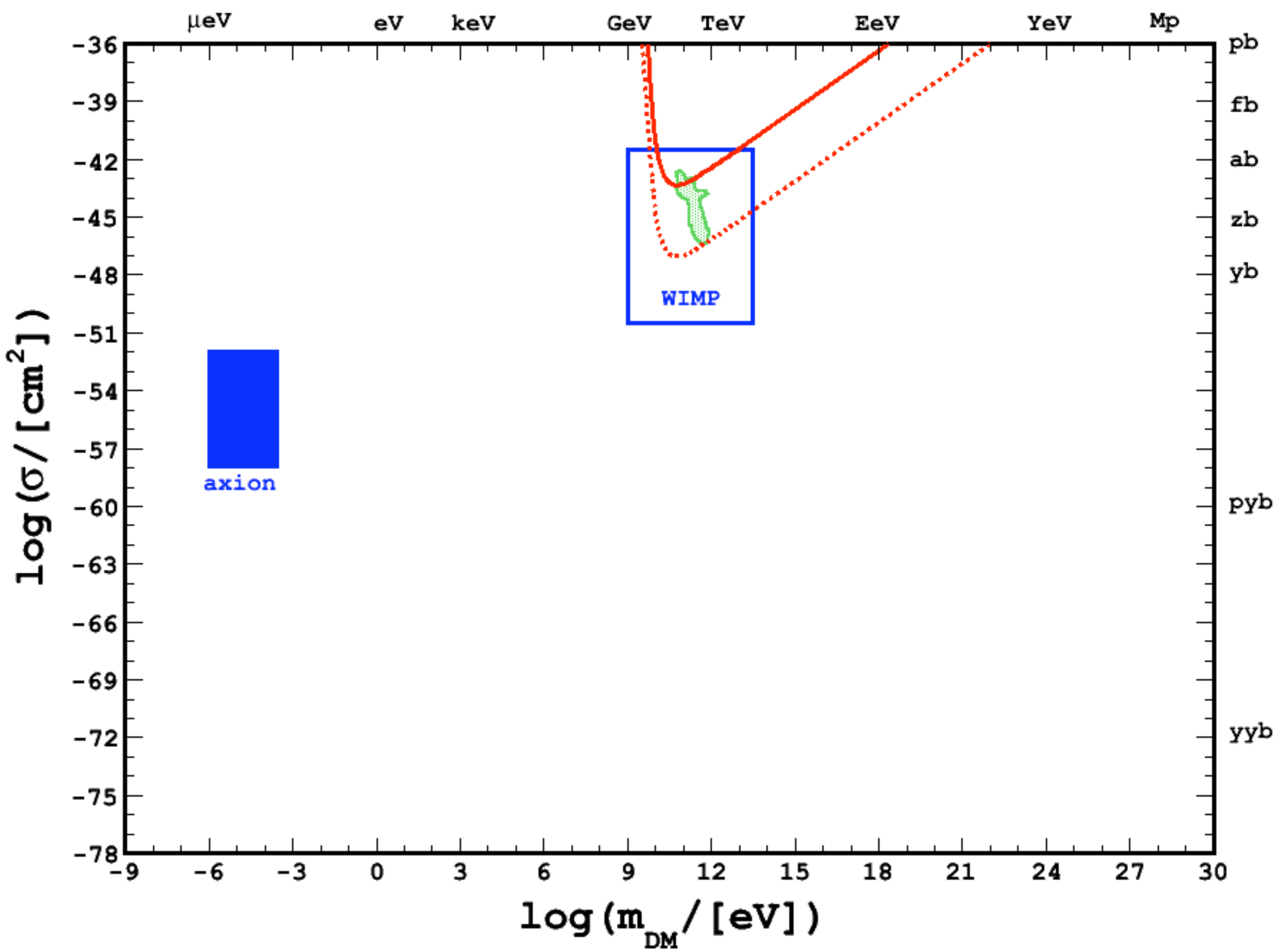
See arXiv:0902.4693 (submitted to PRL)



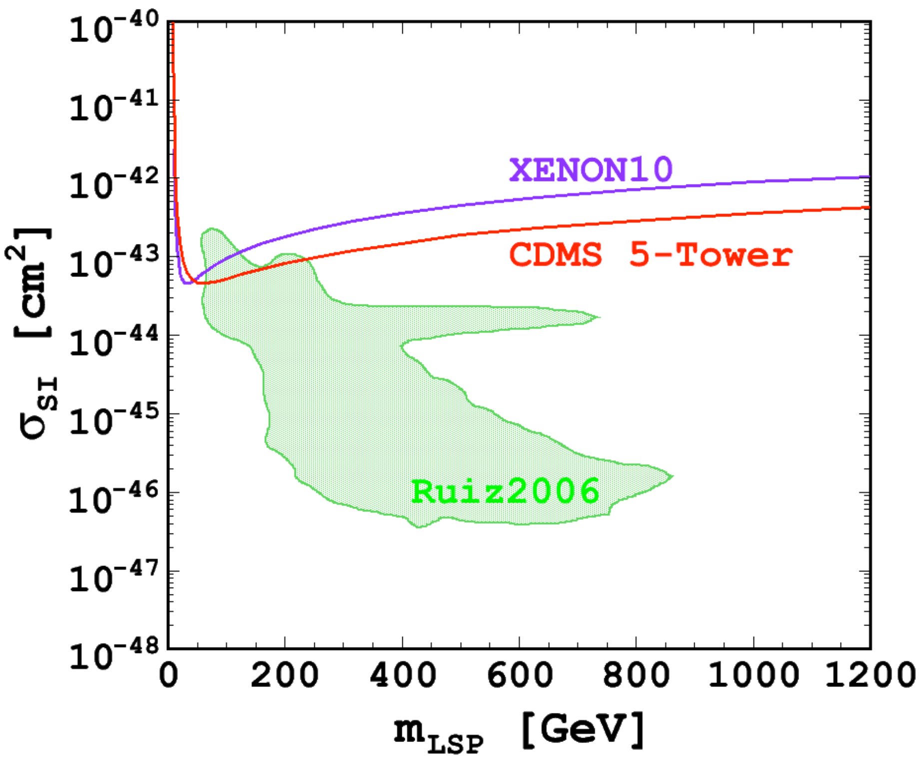


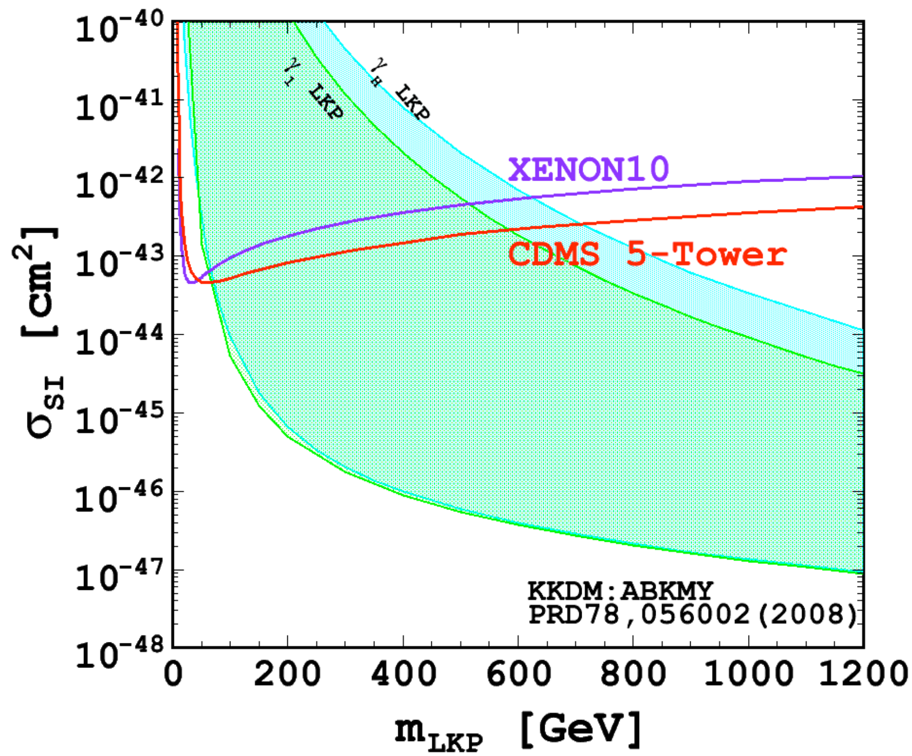
- Searching for the invisible axion models
- For discovery or solar model consistent search
  ➔ $g_{a\gamma\gamma} < 0.5 \times 10^{-10}$ GeV $^{-1}$ (solar ν limit)
- Require 100 kg of detector fiducial volume
  and < 10^{-4} dru of gamma/e background level
  (dru = counts/kg/day/keV)
- The current CDMS gamma background level: ~1 dru

Big Picture : Particle & Astro



Dark Matter Search





- Most models are at $\sigma > 10^{-47}$cm^2
- The goal for the major Dark Matter experiments:
  - ➔ nuclear recoil background level should be controlled less than ~10^{-7} dru (= counts/day/kg/keV)
  - ➔ Current CDMS nuclear recoil background level (world best) : ~10^{-4} dru
- 10^4 times better background control required (with a huge detector volume)!

A Dream in the Real World

10^{-7} counts/day/kg/keV

1 counts/3,000years/kg/10keVs

1 counts/year/3tons/10keVs

A Mission in the Real World

- When you first build a detector (with raw target material and signal readout)
  you will typically have 10~100 Hz of low energy event rate
  by cosmic rays, ambient gammas and internal radioactive contaminations etc

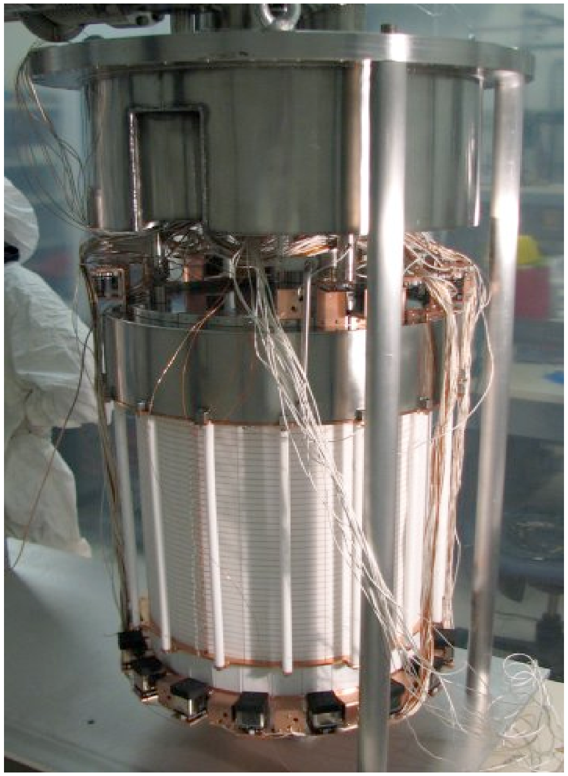
- In order to realize a low background detector (1 event/years/tons/keVs ultra-silent detector)
  ➔ ~10^8 background reduction from the raw detector
  ➔ Gas distillation/purification, material screening,
  deeper site, active/passive shielding …
  ➔ Extremely Challenging !

- Self-shielding is suggested as a solution
  ➔ Shield out gammas and neutrons at the surface of the detector target material
  ➔ Noble liquid detectors : XENON / LUX / XMASS / WArP / ArDM / MAX / …

- Concerns about the noble liquid detectors
  ☑ Background contamination from PMTs ? ➔ QUPID, acrylic vessels …
  ☑ Electron drift above meter scale? ➔ electro-negative purity control …
  ☑ 2nd contamination from the circulation loop ? ➔ closed circulation system …
  ☑ Outgas or vacuum leak? ➔ do better job

Fine Tuning the Existing Recipes

100 kg Dual-phase Xenon TPC
Waseda University (~2002?)
Kamioka@Japan



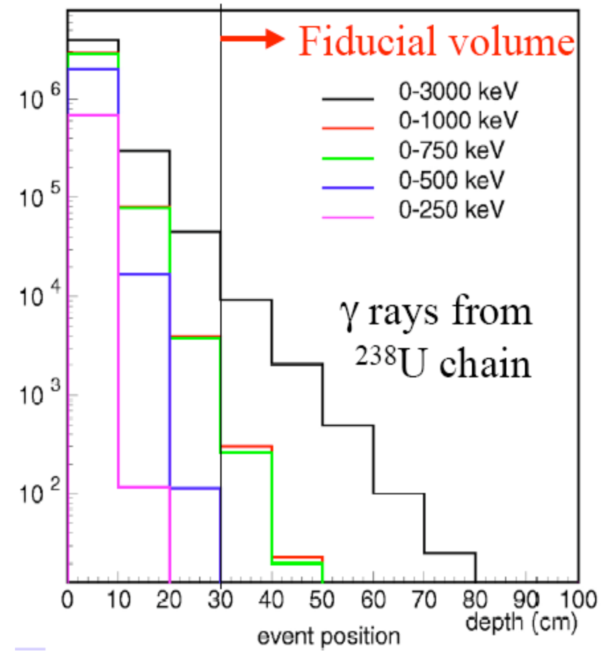
170 kg Dual-phase Xenon TPC
XENON Collaboration (~2009)
Gran Sasso@Italy

300 kg Dual-phase Xenon TPC
LUX Collaboration (~2009)
SUSEL@USA

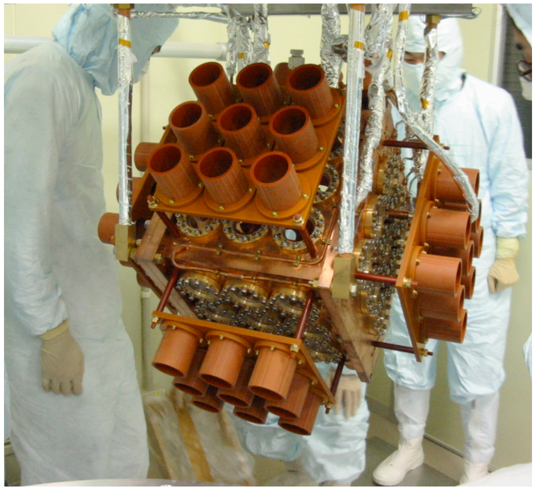
Fine Tuning the Existing Recipes

XMASS : Single phase detector (scintillation light readout)

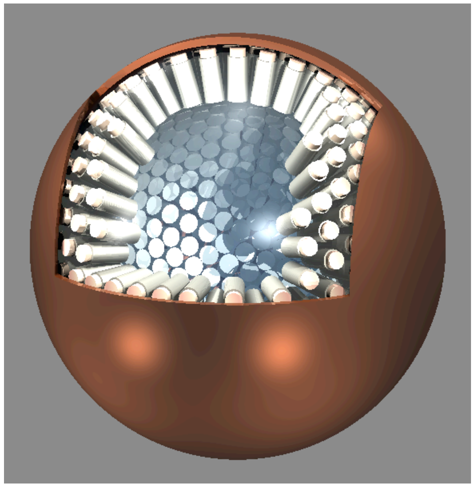
- Kamioka Underground Laboratory, Japan
- 100 kg R&D phase was successful
  Position and energy, self shielding, BG study
- Background reduction plan
  - PMT gammas : self shielding, fiducial volume cut
    10 mBq/PMT (Hamamatsu R10789) achieved!
  - External gammas and neutrons : reduce with water shielding
- 800 kg (100 kg FV) operation will start in 2009

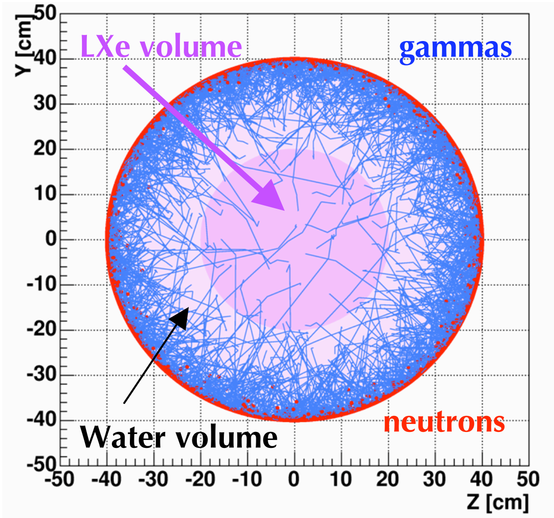


100 kg R&D detector



800 kg DM detector





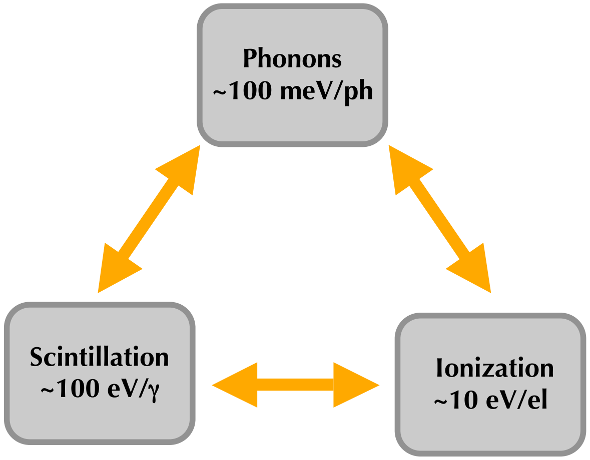
Two Fundamental Questions

1. **How will you make such a low background detector ?**

2. **How will you keep the detector pure ?**

Solid Xenon

Solid Xenon



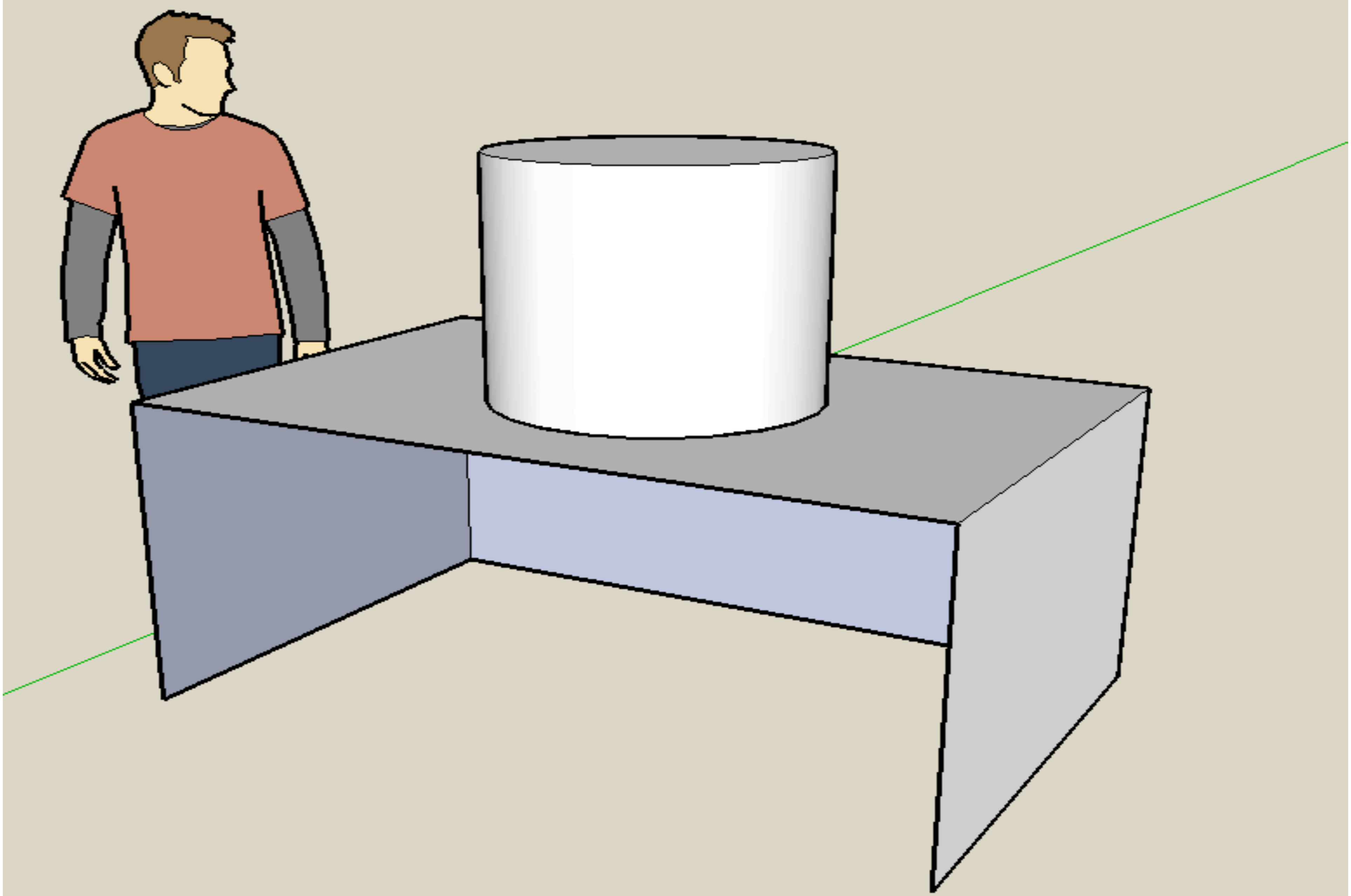
Why Xenon ?

- No long-lived Xe radio isotope (no intrinsic background)
- High yield of scintillation light
- Scintillation wavelength : 175nm (optically transparent)
- Relatively high melting point : T_m = 161K
- Simple crystal structure : *fcc* (same with Ge)
- Easy purification (distillation, etc)
- Self shielding : Z=54

Why Solid ?

- For solar axion search, being a crystal is crucial (Bragg scattering)
- Even more scintillation light (61 γ/ keV) than LXe (42 γ/ keV)
- Drifting electrons is easier in the crystal
- Superb superconducting sensors are running at low temperature (mK ~ K)
- Phonon read out : largest number of quanta (~10,000 phonons / keV)
  - In principle best energy resolution can be achieved in phonon channel
  - Luke-phonon readout will provide ionization energy and position information
- No further background contamination through circulation loop : no Xe circulation
- Optimal detector design for low background experiment
  - Possible container free design
  - No concerns about outgassing and leaks

Imagine



Short History of Solid Xenon (Argon)

1999@Japan
Successful contact of thin Solid Xenon to an ionization sensor using carbon graphite film

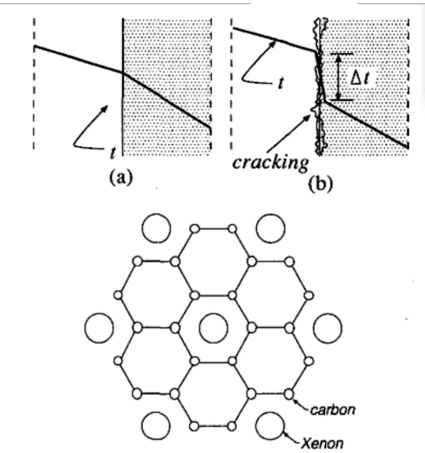
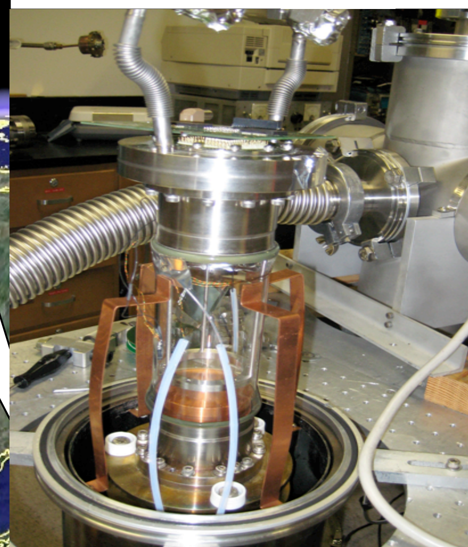


Figure 3: the first xenon layer grown on carbon graphite

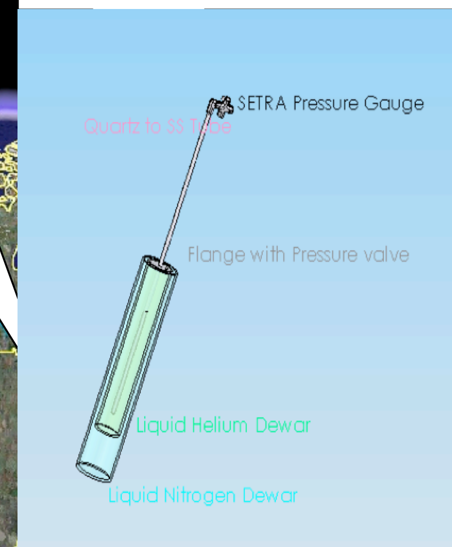
2004@TAMU
Ionization readout from Solid Ar (not Xe). Failed to grow large crystals



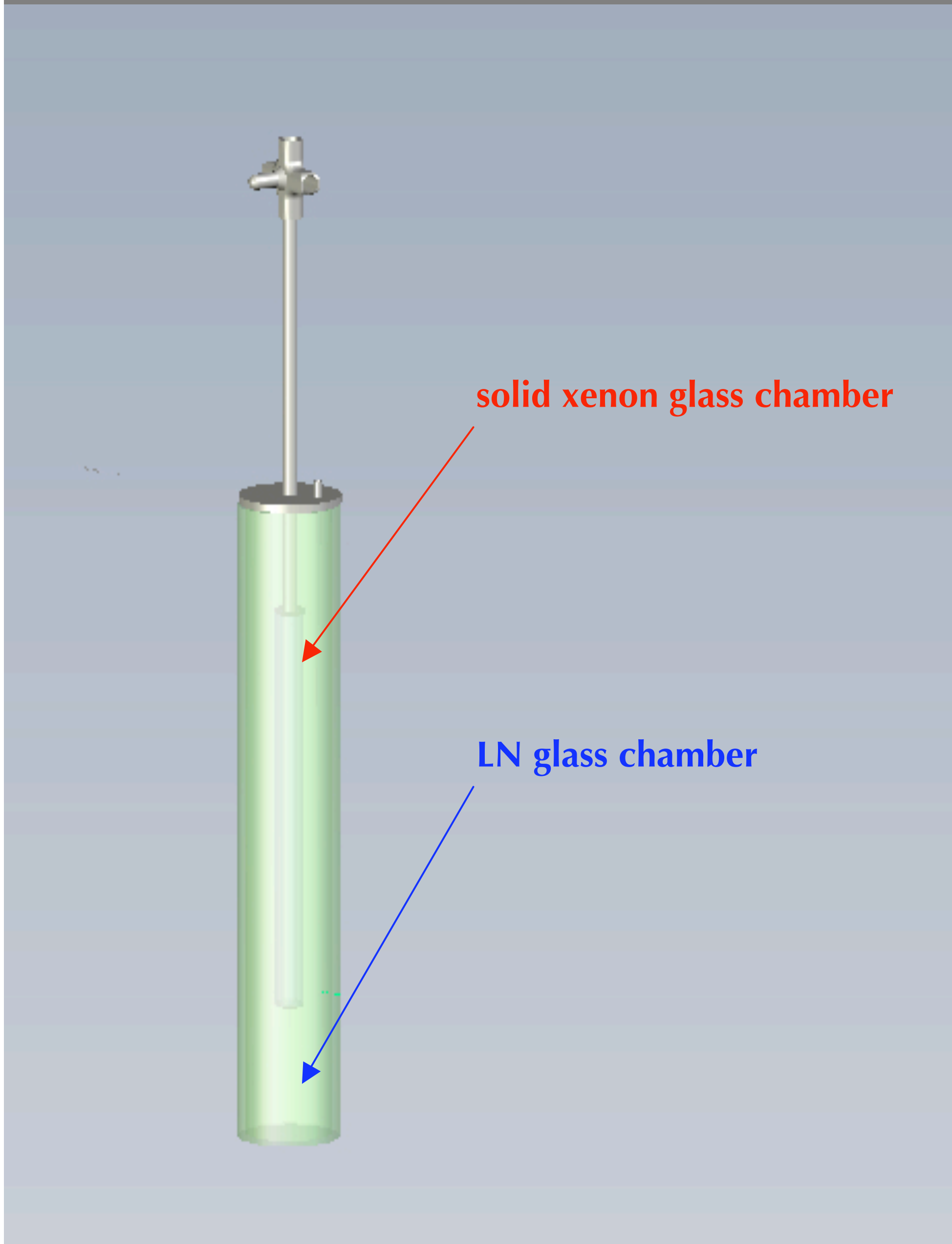
1994@FNAL
Solid Argon detector wasn't successful

2008@FNAL
Solid Xenon Project initiated

2004@Syracuse
A student grew large Xenon crystals everyday without any problem for medical research

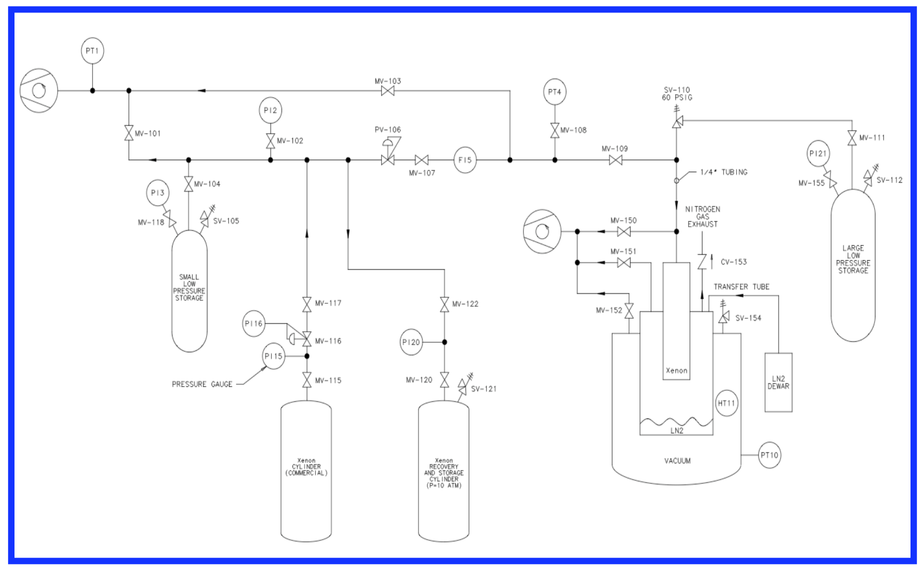


Solid Xenon R&D Phase-I



- Reproduce Syracuse setup
- Grow ~kg size of solid xenon
  (inner chamber capacity : ~10kg)

2008.May : FCPA Review
2008.June : R&D phase-I approved
2008.July-Sep : Design solid xenon system
to fulfill FNAL safety regulation
2008.Oct - 2009.Jan : Mechanical engineering of Stainless Steel chambers (external vendor)

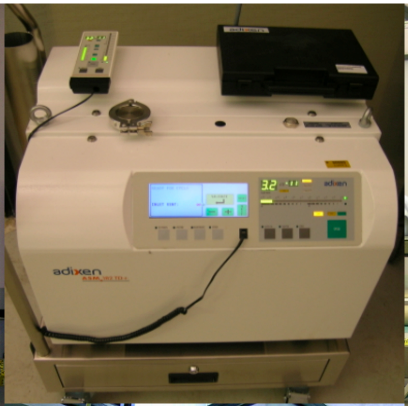


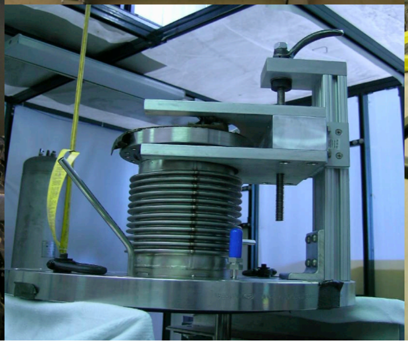
Phase-I: Lab-F@Fermilab

Jan - Mar 2009: Install solid xenon chamber at Fermilab (Lab-F "clean room")
April - June 2009: System check and prepare for the Fermilab safety review
- ➔ **Top flange fabrication at FNAL mechanics shop**
- ➔ **Assemble parts, leak test and system check**
- ➔ **Grow sub-kg size xenon crystal: understand systematic issue**
- ➔ **Grow ~kg size xenon crystal: optical property check**

May - June 2009: Design phase-II systems for large crystal grow and signal readout
- **(1) Prepare full prescription for growing solid xenon crystal**
- **(2) Systematic study for growing solid argon crystal**
- **(3) Propose Phase-II**








Phase-I: Xenon Chambers

Phase-II: Signal readout and larger crystal

1. Scintillation / Ionization readout

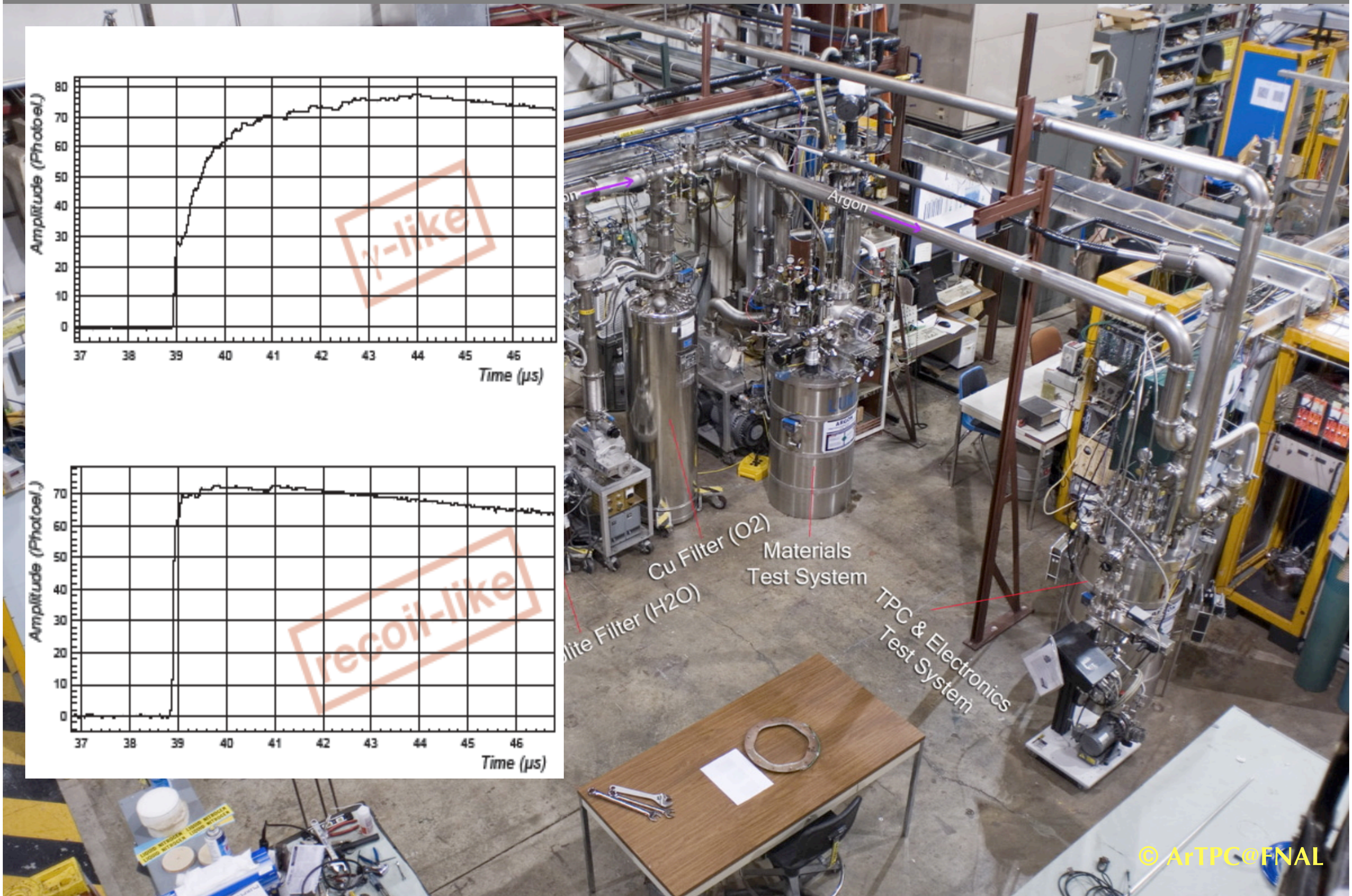
- scintillation readout using standard photon sensors (PMT, APDs…)
- ionization readout by drifting electrons (grid mash)
- use phase-I safety chamber (with high purity quartz vessels)
- xenon purification systems (commercial purifier or build one)

2. Demonstrate large solid xenon crystal growth (~100 kg)

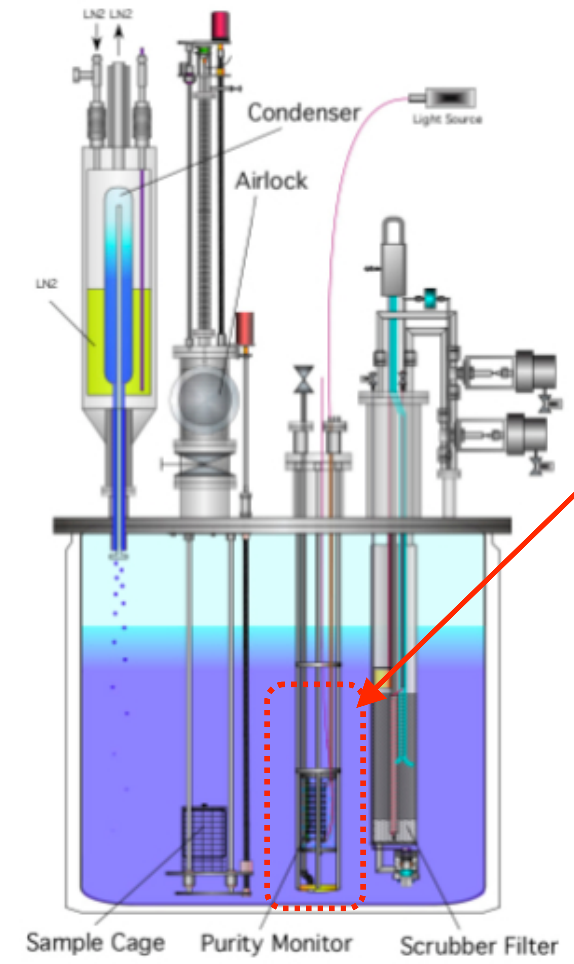
- make a full prescription for growing large solid xenon
- crystal orientation measurement ?

3. Design 10 kg phase prototype detector

Fermilab Liquid Argon TPC test Facility

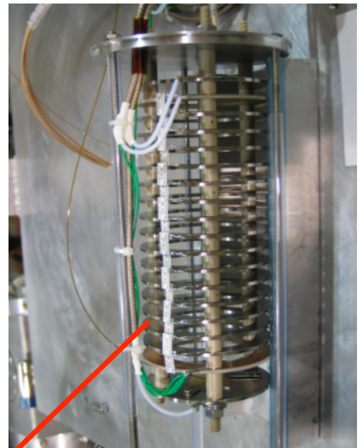


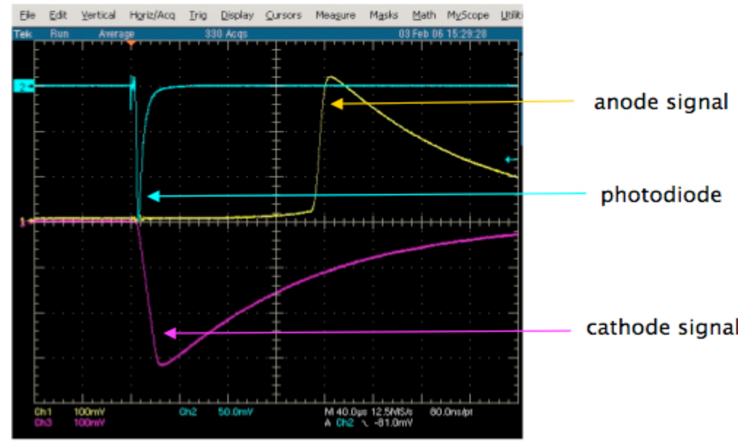
Xenon Purity Monitor



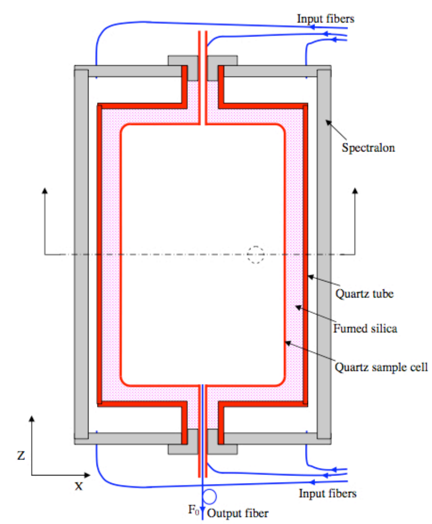
Material test chamber

* Electronegative purity monitor





* Optical purity monitor (new R&D)

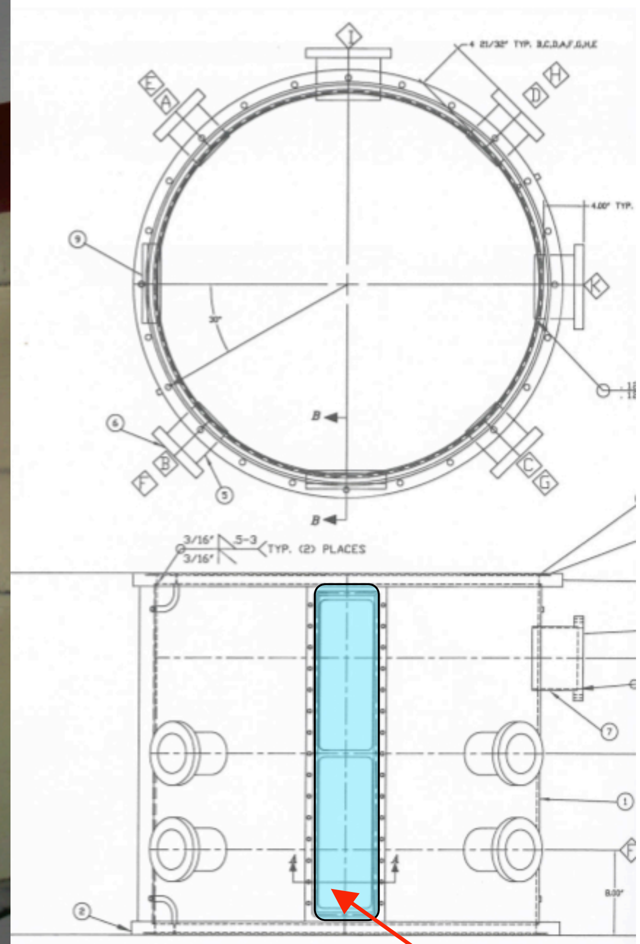


- A new idea for optical purity monitor !
- Integrate Cavity Absorption Measurement (ICAM) ➔ used for oceanography to measure the purity of the water
- R&D issue to find out proper reflector for xenon scintillation light (~175nm)
- NIM paper in preparation for the R&D proposal

Phase-II: Big Vacuum Chamber

Used vacuum chamber at a mechanical vendor: perfect fit for our phase-II R&D

➔ Save substantial amount of design/mechanical engineering time and budget

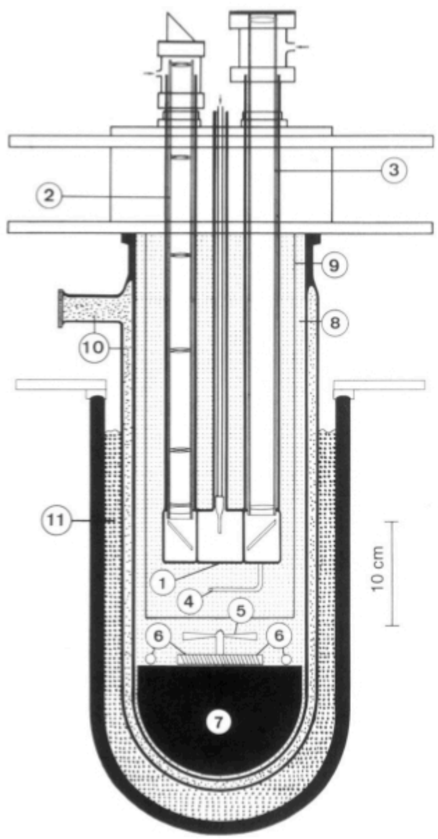


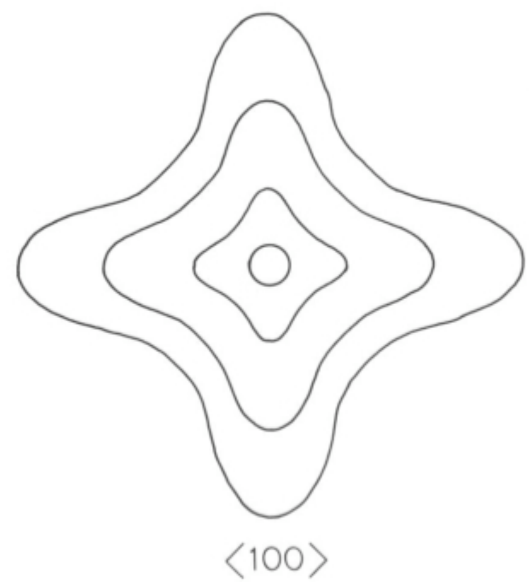
Glass windows

Synthetic quartz vessel
COUPP (@FNAL)

Phase-II: Orientations of the Xenon Crystal ?

- Use the phase-I chambers with minor modification
- X-ray / neutron diffraction measure
- Epitaxial growth of the crystal ?





E. Hurlimann et.al. (1992)

Signal Readout

Scintillation light
- PMT/QUPID/APD …
- Nano-wire / quantum dots (?)
- Transition Edge Sensor (TES)

Ionization Readout
- Grid mash
- Electrodes / Si detector …
- TES

Phonon Readout
- Cryogenics lab
  - Use our collaboration (U.Florida)
- Cold and warm electronics
  - Well studied in CDMS collaboration
- Ballistic phonon readout with TES
  ➔ opens a whole new world!

For phonon readout
Attaching sensors on the solid xenon is the crucial step

Development of a Solid Xe Ionization Chamber

H.Nawa Y.Tamagawa M.Miyajima
Department of Applied Physics, Fukui University
9-1, Fukui 3-chome, Fukui, 910-8507, Japan

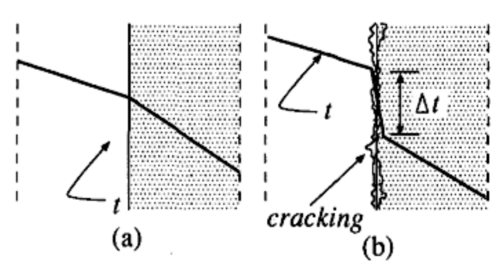


Figure 2: The temperature distribution near the contact surface of solid xenon and metal
(a).Perfect contact, (b).Imperfect contact

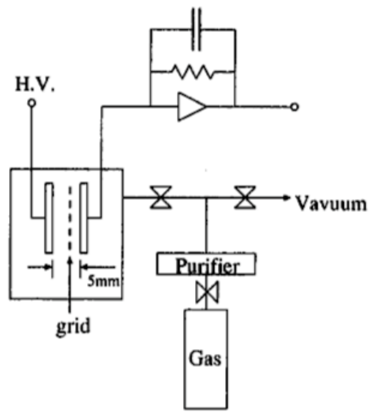


Figure 1: Schematic drawing for a solid xenon ionization chamber and a gas handling system

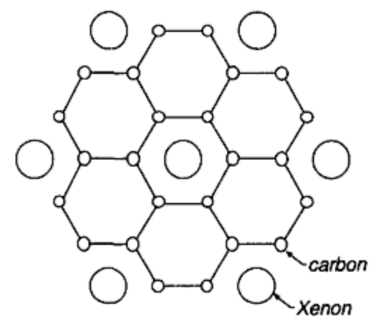


Figure 3: the first xenon layer grown on carbon graphite

Solid Xenon Collaboration

Fermilab
Jonghee Yoo / Dan Bauer / Rich Schmitt / Mike Sarychev

University of Florida
Tarek Saab / Durdana Balakishieva

Texas A&M University
Rupak Mahapatra

MIT
Enectali Figueroa-Feliciano / James Kerman

Columbia
Prof. Elena Aprile (+ a postdoc and a graduate student)

Interest:
Prof. Mitsuhiro Miyajima (Waseda University)
Dr. Alexander Bolozdynya (CWRU)

Specific Questions by FCPA Directorate

(1) Why Fermilab?

a) dark matter, axions, neutrino
b) safety, infrastructure, engineers, technicians, pseudo-infinite support
c) the idea is born at FNAL

(2) What are the risks

a) Technical
Xenon crystal will grow, but how big and how pure?
Phonon readout ? ➔ crucial for $0\nu 2\beta$ decay experiment
b) Management/budget
Xenon price getting cheaper but still very expensive ($4,000~$3,000/kg)!
➔ Any xenon at the Lab garage?

(3) What are the next steps?

Phase-I

Demonstrate ~kg solid xenon (hopefully within June 2009)
Write a full prescription of making xenon crystal

Phase-II

Move the all setup to PAB (currently at Lab-F)
Scintillation/ionization readout (Ar / Xe)
➔measure optical and electric characteristics
Demonstrate scalability of order 100 kg